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Countering A2/AD with Swarming

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Disclaimer

Abstract

The United States wants to fight a war of annihilation because it is well suited to do so. However, the U.S.'s adversaries have a vote in this and have decided that it is in their own best interest to prevent the U.S. from being able to fight such a war. Rather, the adversaries have adopted A2/AD strategies that would force the U.S. to fight an undesirable war of attrition in order to achieve their objective. The current strategy to counter A2/AD is a strategy that forces the tenets of an annihilation strategy into the context of an attrition environment. The result is that it weakens the military as an instrument of national power. The U.S. military should consider swarming as both an effective and efficient strategy for fighting wars of attrition. By incorporating a swarming force into the current strategy, the U.S. military will provide better deterrence and be more coercive during conflict. With those objectives in mind, there are many considerations for how the swarm should be developed and employed. First, the swarm must be attrition tolerant. This can be achieved by utilizing fractionated mass and disposable, unmanned units. Second, the swarm should be low-cost, autonomous, modular, and adaptable. These attributes make swarming a viable solution to addressing the U.S.'s shortfalls in countering A2/AD.

History

Military historian Hans Delbruck proposed there are two general forms of military strategy: the complete defeat of the enemy's military power (annihilation) or the indirect approach of exhausting and eroding a superior power (attrition).[1] Throughout the United States' history, the strategy of annihilation grew in popularity concurrently with the country's ability to wage and win such a war.[2] Russell Weigley termed the U.S.'s penchant for annihilation strategies the *American way of war*. However, the prevalence of smaller, more limited wars during the last half century has often made the costs of an annihilation strategy too great to bear. Weigley writes, "The central theme of the history of American strategy came to be the problem of how to secure victory in its desired fullness without paying a cost so high that the cost would mock the very enterprise of waging war."[3] In the first Gulf War, the U.S. was able to employ a successful annihilation strategy against Iraq and Saddam Hussein. The crushing defeat of the Iraqis served as a clear warning to the U.S.'s adversaries that fighting a war of annihilation would not be in their best interest. In response, many adversaries adopted strategies that would prevent the U.S. from being able to fight a war of annihilation and instead force the superior power to fight a war of attrition. Saddam Hussein had allowed the U.S. to build up and amass its forces in the Persian Gulf in the months leading up to the war. By denying the U.S. access to an area, the inferior nations believed they could exhaust, erode and ultimately attrit the U.S.'s resolve and capability. The U.S. has termed the use of such a strategy as anti-access/area denial (A2/AD).

A2/AD is often used to describe a strategy that seeks to deny access into an area and restrict movement within that area. The term A2/AD is modern, but the concept of preventing an opponent from operating military forces near or in a contested area is as ancient as war itself.[4] Sam Tangredi

Anti-access (A2) - Action intended to slow deployment of forces into a theater or cause forces to operate from distances farther from the conflict than they would otherwise prefer. A2 affects *movement* to a theater.

Area-denial (AD) - Action intended to impede operations within areas. AD affects *maneuver* within a theater.

explains that A2/AD is an approach used by an inferior force when its opponent is feared to have superior strength or skill to such a degree that they would be easily defeated if forced to fight.[5] The theory of A2/AD is that the inferior force can cause the superior force to incur unacceptable costs to access and operate in the A2/AD environment. A superior power may abandon its objectives if an inferior force can deny or delay a decisive engagement through time or attrition ultimately changing the political calculus.[6] Using chess as an analogy, A2/AD can be seen as "preventing the loss of one's own king…by knocking all of the opponent's pieces from the board before the start of the game."[7] As Tangredi notes, "an anti-access vs. counter-anti-access struggle is likely to turn into a war of attrition as well as maneuver."[8] An A2/AD strategy prevents the superior force from bringing enough forces to bear an effective annihilation strategy.[9] Rather, the A2/AD strategy forces the superior force to abandon its annihilation strategy and revert to a costly attrition strategy.

If the United States military loses the ability to gain access to an area, it also loses the ability to project power, which in turns causes it to lose utility as in instrument of national power. Since war is an extension of politics,[10] the need for operational access does not exist for its own sake. Rather, operational access exists to "serve our broader strategic goals… to manage a crisis, prevent war, or defeat an enemy in war."[11] The United States must maintain a credible capability of projecting power in order to protect its national interests and remain a global power. The U.S. military became accustomed to unfettered access but can no longer take the luxury for granted. The proliferation of weapons and diffusion of technology has enabled and emboldened adversaries to contest the U.S.'s ability to access contested areas.[12] Advanced missiles, new fighter aircraft,

inexpensive sea mines, and even computer hackers can make transit through a contested environment vulnerable and riskier. This problem is larger than any single area of operations and could potentially disrupt the balance of power the U.S. has enjoyed for many decades. The denial of access "induces instability, erodes the credibility of U.S. deterrence, can necessitate escalation… and weakens international alliances."[13]

The Current Strategy

The U.S. military's solution to the A2/AD problem is articulated in several documents. The overarching document is the Joint Operational Access Concept (JOAC) which "proposes a concept for how joint forces will achieve operational access in the face of armed opposition by a variety of potential enemies and under a variety of conditions."[14] Released in 2012, the JOAC seeks to provide a framework from which to build doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF). The document identifies 30 operational capabilities the future force will require to counter an A2/AD threat based on a central idea of leveraging "cross-domain synergy." All of these recommendations are based on a set of 11 precepts, or guiding principles.

Operational Access Precepts

- Conduct operations to gain access based on the requirements of the broader mission, while also designing subsequent operations to lessen access challenges.
- Prepare the operational area in advance to facilitate access.
- Consider a variety of basing options.
- Seize the initiative by deploying and operating on multiple, independent lines of operations.
- Exploit advantages in one or more domains to disrupt enemy antiaccess/area-denial capabilities in others.
- Disrupt enemy reconnaissance and surveillance efforts while protecting friendly efforts.
- Create pockets or corridors of local domain superiority to penetrate the enemy's defenses and maintain them as required to accomplish the mission.
- Maneuver directly against key operational objectives from strategic distance.
- Attack enemy antiaccess/area-denial defenses in depth rather than rolling back those defenses from the perimeter.
- Maximize surprise through deception, stealth, and ambiguity to complicate enemy targeting.
- Protect space and cyber assets while attacking the enemy's space and cyber capabilities.

If the JOAC details what the military must do to counter A2/AD, the Air-Sea Battle Concept details how it will do it. Air-Sea Battle was recently renamed the Joint Concept for Access and Maneuver in the Global Commons (JAM-GC). Much like JAM-GC's predecessor, Air-Sea Battle, the strategy focuses on what has worked well in the past, seeking a decisive victory by destroying the enemy's kill-chain - basically an annihilation strategy.[15] David Gompert and Terrence Kelly compare Air-Sea Battle to Air-Land Battle of the 1980s:

> "Akin to the Air-Land Battle plan of the 1980's - meant to thwart Soviet Aggression against NATO - Air-Sea Battle responds to the declining viability of forward defense, combined with an aversion to nuclear escalation…And like Air-Land Battle, there is more to Air-Sea Battle than inter-service collaboration: namely a focus on deep, early strikes against enemy forces, infrastructure, command and control, and territory…"[16]

According to an unclassified overview of ASB, the central idea of the concept is to develop networked, integrated forces capable of attack-in-depth to disrupt, destroy, and defeat adversary forces.[17]

Problems with the Current Strategy

The U.S. military prefers strategies that are akin to annihilation strategies and loathes archaic notions of an attrition strategy. Attrition warfare is widely viewed as an inferior method of fighting within the defense department. Joint doctrine does not even list attrition warfare as a viable means of defeating an enemy.[18] The new American way of war, Max Boot's spin on Weigley's term, "eschews the bloody slogging matches of old. It seeks a quick victory with minimal casualties on both sides. Its hallmarks are speed, maneuver, flexibility, and surprise."[19] The U.S.'s desire to fight war *the American way*, has influenced every aspect of the current strategy and has led to criticism from several scholars.

Air-Sea Battle tries to apply many elements of an annihilation strategy to the problem of countering A2/AD which requires a strategy more akin to attrition. Air-Sea Battle attempts to do what has worked well in the past: using a very expensive and small inventory of weapons to discover and target the enemy's centers of gravity (COG) with the hope that once destroyed, causes the enemy to collapse. One of the guiding precepts of JOAC is that the U.S. military will attack enemy A2/AD defenses in depth using exquisite weapons and delivery systems, such as stealth aircraft.[20] However, this approach may not work well. A superior power may abandon its objectives if an inferior force can deny or delay a decisive engagement through time or attrition ultimately changing the political calculus.[21] When the U.S. risks losing an expensive stealth aircraft or a service member, the decision to utilize the aircraft is heavily weighed. This is very similar to the issues identified by Weigley in 1973; "the central theme of the history of American strategy came to be the problem of how to secure victory in its desired fullness without paying a cost so high that the cost would mock the very enterprise of waging war."[22]

The reluctance to use force emboldens adversaries to constantly probe for the U.S. red-line. When it appears the U.S. is unlikely to react, adversaries are less deterred. If on the other hand, the U.S. is perceived to respond with "early and deep attacks", there is an increased likelihood a crisis will escalate. This assumption is even more problematic when dealing with nuclear-armed states, such as China. The JOAC specifically states "attack enemy A2/AD defenses in depth rather than rolling back those defenses from the perimeter."[23] Such an act would be likely to cause a large military response and could easily escalate a minor crisis into war. Furthermore, this notion conveys a message to adversaries that the U.S. may pose an existential threat to their survival. While there are times this type of posturing is required (i.e. nuclear deterrence) such an approach may cause an adversary to "feel a need, out of self-defense, to launch [preemptive]

attacks even if they had not planned to start a war."[24] In short, the current strategy does not sufficiently deter adversaries, and if deterrence fails, it may cause the crisis to escalate.

The other major problem is that the military's current strategy is expensive and relies on a small inventory of weapon systems, which makes it less suitable for countering an A2/AD strategy. The rising costs of these exquisite weapons systems are creating a cost-curve problem for the Department of Defense (DoD).[25] By relying on exquisite and expensive weapon systems, the military is not suited to sustain a drawn-out war of attrition that may be required to counter an adversary's A2/AD strategy. Sam Tangredi goes on to explain the heart of the problem with the disconnect between what the defense department is buying compared to the reality of countering A2/AD:

> "Preparation for a counter-anti-access campaign cannot consist of building a small, very expensive inventory of precision weapons. The more precise a weapon, the more operationally effective it is. But it is the robustness, sustainability, and survivability of the overall force - with built-in redundancies, which can act as alternatives when specific capabilities are neutralized - that are the requirements for effective counter-anti-access…Weapon systems must be able to conduct sustained attacks, not just precise attacks, in order to defeat a high technology anti-access network."[26]

By being expensive and limited in numbers, it is difficult for the current U.S. strategy to efficiently target an adversary's A2/AD strategy. The adversary is well aware of this and uses this limitation to their advantage. Gompert and Kelly recommend that the U.S.'s counter A2/AD strategy should use forces that are more survivable, sustainable, distributed, networked, numerous, elusive, small, long-range and hard to find.[27] The two argue that such a force would overwhelm and confuse an

adversary's targeting. A force with these characteristics would be best suited for an attrition strategy and therefore would be ideal for countering A2/AD.

Scholars and critics such as Tangredi, Gompert, and Kelly have described the ideal force for countering A2/AD and contrasted those requirements to the current force structure under the JOAC. There are stark differences as seen in illustration below:

JOAC (Annihilation Strategy)	COUNTER A2/AD (Attrition Strategy)
Few # weapon systems	Large # weapon systems
Multi-role weapon systems	Single-role weapon systems
Expensive systems	Inexpensive
Long procurement cycle	Made on demand
Slow adaptation	Agile adaptation
Survivable - stealth	Survivable - redundant
Manned	Unmanned

Historically, adopting an attrition strategy required massing large formations. Fighting wars of attrition with mass usually required a great deal of blood and treasure. John Arquilla and David Ronfeldt explain how fighting evolved from melee, to mass, to maneuver. Melee fighting is characterized by individuals fighting in a non-cohesive manner. Melee evolved into mass with the advent of written orders, signal flags, and radio communication.[28] Massing had the benefit of organization. Mass evolved into maneuver fighting with the advent of means of rapid mobilization and coordinated command and control.[29] Maneuver warfare is the U.S.'s modus operandi. However, if an adversary successfully executes an A2/AD strategy, maneuver warfare becomes ineffective and the war reverts back to fighting in a way that is more characteristic of mass.

Restated, the U.S.'s maneuver style of fighting is of little use in an A2/AD environment. Fighting in an A2/AD environment requires elements of mass. Typically, fighting in mass is a characteristic of an attrition strategy - the strategy the U.S. has long abandoned.

Proposed Solution

Nearly 30 years ago, John Mearsheimer recognized that "Substituting technology for manpower is a time-honored solution which certainly has a rich tradition in the United States."[30] Continuing this time-honored solution, advances in technology have made it so that the U.S. could adopt a "best of both worlds" strategy that combines the tenets of maneuver warfare with those of mass warfare. A swarm uses a combination of mass and maneuver for amazing synergetic effects.

In addition to the work of Arquilla and Ronfeldt, Paul Scharre has written several works on swarming. The three explain that swarming combines the highly centralized nature of melee combat with the mobility of maneuver and the cohesion of mass.[31] Swarming is not just a large number of systems in an uncoordinated attack—that is a deluge or a riot. Rather, a swarm is capable of coordinating many simple units in order to adapt to the environment and collectively accomplish something far more amazing than any individual unit could alone. Some of the most successful species in nature have mastered swarming. Scharre uses ants to illustrate the power of swarming. "Ant colonies can build structures and wage wars, but a large number of uncoordinated ants can accomplish neither."[32]

A military swarm would be comprised of many small, unmanned, networked platforms. These platforms are individually less capable of defeating an enemy but in aggregate provide far more combat power. Drone swarms are unmanned which allow for greater mass with less risk and cost. Recent convergences in robotics, information systems, and communication networks has allowed the once science-fiction swarm to become a reality. In fact, the Pentagon's secretive

Strategic Capabilities Office publicly acknowledged the successful testing of drone swarms during an exercise in 2015. These drones were launched from flare canisters, able to locate each other, gain situational awareness, and conduct surveillance.[33] DARPA recently announced it was working on developing swarms with "modular-payload capabilities for tailoring the cameras, sensors, and electronics to specific missions, [able to] communicate with each other to coordinate their work, and transmit data via satellite back to bases for analysis."[34]

Swarming may be able to address the shortfalls in the current counter A2/AD strategy because it could reintroduce mass onto the battlefield which in turn would allow the U.S. to employ either or both an annihilation and attrition strategy. Some advantages of swarms include dispersal of combat power, resiliency over survivability, graceful degradation of combat power instead of catastrophic losses, combining sensors with shooters, and the ability to saturate enemy defenses.[35] However, the characteristics of an unmanned swarm must be tailored under an over-arching strategy. A swarm designed to counter an opponent's A2/AD strategy should be aligned with the objectives they are trying to achieve—both tactical and strategic. To best design a counter-A2/AD swarm a swarm must be integrated into the current strategy, not act as a replacement.

The following recommendations are addressed at two shortfalls in the U.S.'s current counter A2/AD strategy. The first is to use swarming such that it deters adversarial aggression. The second is to use swarming in a way that it is capable of coercing an adversary. Combined, these two changes will provide political leaders with a wider range of military options in response to an adversary's actions. Each of these objectives have been noted by scholars and critics as shortfalls in the current Air-Sea Battle strategy and each could be addressed by incorporating swarming.

Deterrence

Deterrence is the threat of force in order to discourage an opponent from seeking its objective. Successful deterrence requires a capability, credibility, clear communication, and rational decision making.[36] However, these requirements are usually difficult to orchestrate when dealing with deterrence in a non-nuclear scenario. Conventional deterrence is largely based on perceptions. Creating the wrong perception can cause conventional deterrence to fail, as critics argues is the case with Air-Sea Battle. If the U.S. elects to target the enemy's kill-chain with early and deep attacks, there is an increased likelihood a crisis will escalate. This assumption is even more problematic when dealing with nuclear-armed states, such as China. While the JOAC specifically states "attack enemy A2/AD defenses in depth rather than rolling back those defenses from the perimeter," such an attack carries the risk of escalating a minor crisis into a war. This leaves politicians with fewer military options when dealing with adversaries that are employing A2/AD strategies. For conventional deterrence to work, the U.S. must present a resilient force posture that removes the incentive for a pre-emptive first strike. Solomon writes in regards to Air-Sea Battle, "Any U.S. doctrine predicated upon executing a conventional first strike would severely risk undermining deterrence by incentivizing preemption in a crisis. A reactive doctrine grounded in force resiliency may actually be stronger from a grand strategic perspective."[37] Soloman goes on to write:

> "Defenders can obtain conventional deterrence by denial if an opportunistic antagonist is *convinced* that the defender possesses conventional forces of *sufficient capability*, *quantity*, readiness, and proximity to the contested area to ensure any conceivable conventional offensive by the antagonist stands an unacceptable chance of degenerating into a costly, *risky, protracted, and indecisive* conflict. (*emphasis added*)"[38]

The U.S.'s adversaries already perceive that a direct, head-on engagement with the U.S. military will most likely result in the annihilation of their military power. This is why they adopt A2/AD strategies which deny such a decisive, culminating battle from ever taking place. By preventing such a battle from taking place, the adversary removes the prospect of quick annihilation and forces the U.S. to accept exhaustive attrition. The adversaries perceive that U.S. is not willing to fight a war of attrition (red line 1) and that the U.S. does not want to fight an all-out war over a limited objective (red line 2). The gap between these two red lines is where adversaries feel emboldened and deterrence fails. The U.S. must close the gap between the two red lines and it can do so by making adversaries believe that the U.S. is in fact willing to fight a war of attrition.

A very important distinction should be made at this point. The swarm does not have to necessarily defeat an enemy's A2/AD strategy. Rather, the swarm needs to only create a perception that the U.S. is willing to fight within the A2/AD environment and accept its losses. The difference is important to highlight because so much of the DoD's strategy is focused on defeating an enemy; this approach highlights the value of accepting a war of attrition. Therefore, the ability to counter an adversary's A2/AD strategy is a deterrent to war when it denies them the ability to easily attain their political objective**.**[39] "It is unlikely that a state's decision-makers will opt for war if they envision a lengthy war of attrition - even if they believe they will ultimately prevail."[40] Therefore, the key to countering an A2/AD strategy is fielding and sustaining a force capable of making any conflict difficult and protracted. Tangredi argues,

> "It is the robustness, sustainability, and survivability of the overall force…that are the requirements for effective counter-anti-access…Weapon systems must be able to conduct sustained attacks…in order to defeat a high technology anti-access network."[41]

These attributes are the hallmarks of attrition warfare.

A swarm can fight a war of attrition because of an *attrition tolerant* design. A swarm that is attrition tolerant can accept losses and still continue its mission. This concept can also be referred to as overmatch. Carl von Clausewitz recommended superior numbers in combat to overcome the effects of attrition and achieve victory.[42] He highlighted that Napoleon Bonaparte won all of the battles when numerically superior, but lost all of those when inferior.[43] Napoleon respected the benefits of mass and elected that his naval forces be at least 20% stronger than the opposition.[44] Swarms offer one of the most viable means for fighting a war of attrition because, as Scharre explains,

> "Low-cost uninhabited systems can be built in large numbers, 'flooding the zone' and overwhelming enemy defenses by their sheer numbers…the result will be a paradigm shift in warfare where mass once again becomes a decisive factor on the battlefield."[45]

Swarm utilize "Greater numbers of systems to complicate an adversary's targeting problem and allow for graceful degradation of combat power as assets are attrited."[46] Designing a truly attrition tolerant swarm requires several calculations.

First, planners will have to consider the attrition capability of the enemy; in this context, the attrition rate in an A2/AD environment. The attrition rate is calculated by estimating the probability of kill per engagement. The probability of kill (P_K) is "the statistical probability that a weapon will detonate close enough to its target with enough effectiveness to destroy the target."[47] The P_K is measured from zero to 1, with 1 being a perfectly effective defensive system.[48] The most formidable weapon systems can achieve P_K values up to 0.9.[49] However, a P_K of 1 is believed to be impossible.[50] In-depth study of the enemy's capability results in a P_K value suited to particular A2/AD defensive systems. After a P_K value is determined, the planner's next step is to anticipate

the total number of engagements over a period of time (such as hours, days, months, or possibly even years).

The total number of engagements is limited by *opportunity* and *available ammunition*. The opportunity assumption must consider a range since the defender holds the ultimate decision on when to engage. Air-Sea Battle focuses on decreasing the enemy's opportunity by designing exquisite systems with low observability and enhanced survivability.[51] While opportunity is difficult to estimate, the amount of available ammunition is not. The attrition rate is estimated with knowledge of an enemy P_K value, total opportunities, and supply of defensive weapons. Based on this estimation, the swarm is scaled to tolerate attrition without experiencing complete mission loss.

At first glance, it may seem intuitive to scale the swarm with at least a one-for-one requirement. Meaning for each round of available ammunition (i.e. one surface-to-air missile) one individual unit in the swarm is required. However, this intuition is wrong because of the concept of compounding probabilities.[52] To illustrate, consider a counter-A2/AD swarm consisting of ten units, each capable of successfully accomplishing the mission independently. Also, suppose the A2/AD defense has an individual employment P_K of 0.9 and fires upon the swarm at every opportunity. If the defender wants a high confidence (a 95% chance) that their A2/AD will defeat the swarm, probability analysis states that they will have to employ nearly 23 times. The reason for the unexpectedly large number of defensive shots is that not all missiles will confidently hit their targets.[53] [54] With the same assumptions, a swarm of 100 units requires 329 defensive shots.[55] If the defender can only fire 200 shots against the swarm because of the physical limit of available ammunition, the chance of confident mission success is drastically reduced to 40%. If only 150

shots can be fired at the swarm, confidence is at a mere 10%.[56] This example illustrates the powerful effect of mass: the significant decrease in the probability of a successful defense.

A truly attrition-tolerant swarm would be composed of disposable units that can be lost without impacting the overall chance of mission success. For a unit to be disposable, it should be unmanned. Unmanned systems are capable of taking on a greater degree of risk and are often said to be best suited for jobs that are dull, dirty, or dangerous. In 2011, an MQ-1 Predator was the first remotely piloted asset to successfully conduct a destruction of enemy air defense (DEAD) mission.[57] The main concern with disposable systems is the loss of sensitive information. This problem is exaggerated by the exquisiteness of the system lost. For example, the RQ-170 that Iran claimed to have captured may have had a great deal of sensitive technology and information on board.[58] However, simple systems can be designed so that information is passed in real-time and never stored on board the unit. Such a design mitigates the damaging effects of losing a weapon system and allows the swarm to be attrition tolerant.

By designing a swarm that is attrition tolerant, the U.S. can showcase to its adversaries that is now willing to fight a war of attrition. The swarm itself does not have to be capable of defeating an adversary's A2/AD strategy. Rather, it simply has to flip the burden of fighting a war of attrition onto the adversary.

Coercion

Coercion (or compellence) is the use of force to manipulate the costs and benefits of some action in order to change the behavior of a state. The degree to which a state refuses to change their behavior can be a function of the following formula published by Robert Pape:

$$R = [B * p(B)] – [C * p(C)]$$

R = value of resistance; B = potential benefits of resistance; p(B) = probability of attaining benefits; C = potential costs of resistance; p(C) = probability of suffering costs. Concessions occur when R < 0[59]

Based on this formula, strategies can be classified based on which aspect they attempt to affect. Denial strategies attempt to lower the probability of attaining benefits (pB), punishment strategies attempt to increase the costs of resistance, and risk strategies attempt to increase the probability of suffering costs. Pape's conclusion is that throughout recent history, the most successful coercive strategies have been denial, or those that focus on undermining the state's confidence in its own military strategy.[60]

The military strategy that adversaries have confidence in is their A2/AD strategy. Again, these adversaries realize that facing the U.S. head-on is a fool's game. This illustrates why states employ A2/AD strategies in conjunction with other limited objectives.[61] Stated differently, an adversary's A2/AD strategy is a center of gravity because it is the "source of power that provides moral or physical strength, freedom of action, or will to act."[62] Therefore, undermining a state's ability to successfully wage an A2/AD campaign could cause the loss of confidence in their ability to hold off the superior power and ultimately to discontinue pursuit of their objective. Under the deterrence section, it was argued that the U.S.'s strategy did not need to be able to defeat the enemy's A2/AD but rather create a perception that it was willing to try. To be coercive, the strategy must actually be able to defeat the effects of an enemy's A2/AD. The current strategy cannot do this alone because the costs would be too great. Swarming offers a means and a way to fight at a far lower cost. When the two strategies are combined, there is an amazing synergy that can be obtained. The ability to easily undermine an adversaries' A2/AD strategy would have a powerful coercive effect.

In order to make it easy to undermine an adversaries' A2/AD strategy, the swarm must provide a low cost-exchange ratio such that the cost of utilizing the swarm is far less than the cost of countering the swarm. "If it costs markedly less for us to defeat a missile than it does for the

adversary to build and launch it, the strategic calculus changes significantly."[63] There are several steps and technological considerations for making the swarm low cost.

First, the planner analyzes the defender's costs and establishes a budgetary ceiling for the maximum cost of the swarm. The SA-20 Gargoyle surface-to-air missile system presents an excellent example. Suppose that the previous example of a 100-unit swarm (requiring 329 defensive shots) is able to completely deplete an SA-20 division.[64] [65] Each shot from an SA-20 costs approximately $1M.[66] Comparing the total swarm units to the defender's total employment cost, a maximum swarm per-unit cost (a budget ceiling) is found.[67] The table below shows the cost-exchange ratio between the swarm and the SA-20:

Offensive Swarm			**Defensive A2/AD**				**Probability**
Variant	**Units Required**		**Type of Weapon**	**P_K (P_L)**	**Cost Per Shot**		**Shots Required**
1	100	vs.	9M96 Missile (SA-20)	0.9 (0.95)	$1M	=	329
BUDGET $3.29M Max Cost per Unit				**Cost Exchange Ratio** $329M ÷ 100 units			**Total Cost** $329M

The primary challenge for the planner is to procure a unit that is mission-capable yet below the budget ceiling. The assumption so far has been that each unit must be capable of completing the mission - the meaning of "1 variant" in the table. This requires each unit to have robust capabilities much like our current exquisite air, land, and sea mechanized forces. Paul Scharre writes that the U.S. military must "change the notion of qualitative superiority from an attribute of the platform to an attribute of the swarm."[68] One of the U.S. Air Force's least expensive systems, the MQ-1 Predator (at approximately $5M), would violate this budget ceiling yet would not carry

all of the redundant capabilities necessary in the A2/AD environment.[69] The challenge for the planner is to field a technology that can stay within this budgetary constraint yet accomplish the mission. If successful, the planner attains an advantageous cost-exchange ratio over the defender and undermines the A2/AD strategy.

To reduce the costs of individual units, fractionation of capabilities must be dispersed within the swarm as opposed to duplicating large, exquisite units (single variants, such as the MQ-1 Predator).[70] Fractionation is the concept of distributing capabilities among units under a cooperative behavior. The individual units contribute only a portion to the overall capability of the swarm. Cooperative behavior requires a form of communication or task recognition within the swarm to be able to maintain near-continual activities within the A2/AD environment.[71] The swarm operates in the A2/AD environment with the confidence that while some units are attrited, the cooperative behavior ensures mission accomplishment. By making each unit less complex, the actual cost per unit can be reduced.

The fractionation of capability into subcomponents will result in the individual units being simpler than traditional weapon systems. The exquisitely complex system is the result of the need to physically house many other capabilities and redundancies. This aggregation imposes limitations as well as increases the cost per additional capability. For example, one MQ-1 Predator can carry two Hellfire missiles. A requirement for a third missile requires an additional Predator, a 100% cost increase. Adding additional capabilities within the fractionated swarm would not require adding all the additional capabilities to an exquisite weapon system. For a 100-unit fractionated swarm, adding one more weapon corresponds to a 1% increase. Fractionating offers a more cost-efficient strike package.

The key to building a fractionated swarm is utilizing a modular design for individual components. Modular components allow the swarm to be outfitted with the exact capabilities for the mission. Examples of modular components include basic airframe structure, payload, propulsion system, and control system. Modularity allows for rapid fielding of weapon systems by tailoring the capabilities to the changing requirements. The wings and propulsion can be outfitted to support long-range and endurance or short-range and speed. The payload can be suited to the type of information that is required. Continuing the example, the modular unit can be outfitted to be either a sensor or a shooter. The sensor unit could have a camera payload and a long-endurance motor/wing. The shooter unit could have a warhead and high-speed motor/wing. Disaggregating an exquisite system into a swarm of its constituent capabilities reduces costs because redundancies and capabilities that may have been necessary within the exquisite system are no longer required. Furthermore, modularity inherently requires interoperability, which also reduces costs.

However, fractionation erodes the advantages of mass and makes the swarm less survivable.[72] For instance, continuing the same 100-unit example, now assume the swarm is fractionated with two variants: 50 units have the sensor capability (i.e. find, fix, track, assess), and 50 units have the shooter capability (i.e. target and engage).[73] Previously, the swarm consisting of 100 complex units drove the defender to employ 329 defensive shots to have 95% confidence.[74] But when the swarm is fractionated with two separate variants, the 95% confidence rate can be achieved with only 230 shots.[75] The reason the number of shots decreases is because the defender only has to destroy one variant group from the entire swarm to cause mission failure. If fractionated to three variants, only 184 shots are required; four variants requires 160 shots, and so forth.[76] Clearly, the advantages of mass and attrition diminish drastically when capabilities are fractionated. To compensate for the shortfall of fractionation, the swarm must be scaled to a larger

number, thus increasing the overall cost. In order to return the weapon expenditure rate to the non-fractionated level, the two-variant swarm must be increased from 100 to 136 units.[77] Three-variant swarms must be increased to 162 units and 4 variants to 180 units.[78] However, increasing the number of units decreases the maximum cost per unit from \$3.29M to \$2.42M such as in the 2-variant swarm shown in the table below.[79] Luckily, each variant should cost considerably less than the more exquisite single variant system. For example, a sensor unit may only cost 25% of what a combined sensor-shooter system costs because simplification removes design constraints inherent in aircraft or other complex, high performance systems.

Consolidated Cost-Exchange Ratio Table								
Offensive Swarm				**Defensive A2/AD**				
Variant	**Units Required**	**Max Cost per Unit**	**Total**	**Type of Weapon**	**P_K (P_L)**	**Shots Required**	**Cost Per Shot**	**Total**
2	136	**\$2.42M**	**\$329M**	9M96 Missile (SA-20)	0.9 (0.95)	329	\$1M	**\$329M**

Finally, the planner can determine a relative budget ceiling for each fractionated unit in the swarm—key knowledge to building a cost-efficient swarm. As the swarm increases in size, the budget must decrease to maintain an advantageous cost-exchange ratio versus the particular A2/AD defense. The table below shows an appropriately sized swarm and the associated budget ceilings per fractionated swarm units compared to various surface-to-air missile costs.[80] The table assumes a high P_K to illustrate defender technology advancement. With this knowledge, the planner can theoretically calculate the swarm size to ensure the efficient use of mass within the A2/AD environment.

Swarm Size for 329 Shots (0.9 P_K, 95% confidence)		Budget Per Swarm Unit		
Variants	**Units Required**	**Black-Market MANPADs $5k per shot**	**9K38 Missile (SA-18) $60k per shot**	**9M96 Missile (SA-20) $1.0M per shot**
1	100	$16k	$197k	$3.29M
2	136	$12k	$145k	$2.43M
3	162	$10k	$124k	$2.07M
4	180	$9k	$111k	$1.85M

The prudent planner should anticipate that a defender will decrease their cost-per-shot through strategy or over time.[81] Technological advances in directed energy could drastically alter this calculus because the cost per shot would be significantly reduced. However, additive manufacturing (or 3D printing) could allow for the rapid adaptation of units. Raytheon has proven the ability to print 80% of a guided missile, including the seeker components as well as the rocket motors.[82] Many industrial components can now be manufactured using advanced plastics that have the strength of metal. This ability to adaptively manufacture can enable the U.S. to win the "learning contest" faster than the adversary. For example, by changing the shape of one system, the radar cross section (RCS) can be altered so that the subsequent salvos confuse the enemy and negate their attempts at innovative countermeasures.

The swarm may cost less but it also has to be operationally effective. It is safe to assume that space and cyber will be contested in an A2/AD environment which could reduce the U.S.'s ability to command and control a force. A swarm is able to continue operating with degraded human control. Today's autonomous systems are predominantly rule-based platforms which repeatedly perform defined actions without consideration to the environment. However, the trend

is towards the development of programming which allows for behavior to change based on internal and external influences. "DARPA…successfully demonstrated the ability of a network of cooperating uninhabited aircraft to cover an area for reconnaissance purposes, autonomously re-tasking assets to cover areas of interest based on warfighter input."[83] Some of the more novel approaches involve emergent behavior, neural networks, and subsumption architecture.[84] Emergent behavior control models autonomy after animals in nature that cooperate without direct signaling, such as flocks of birds or schools of fish. Emergent behavior could be very useful in a contested environment because the units could still work together within a degraded electromagnetic spectrum (EMS). Neural networks learn behaviors by evaluating their past behaviors to improve future behavior. Finally, subsumption architecture allows each unit to behave in a self-optimizing manner and then coordinate with other units when it has the ability to do so, parallelizing the behavior of a swarm at the lowest level. These advances in automation will allow the swarm to be more resilient and capable of projecting power despite degradations to the EMS.

Projecting a force in mass is more difficult in an A2/AD environment because the "tyrannies of distance" coupled with the anti-access measures compound logistical problems. Therefore, if a planner is going to effectively present an attrition tolerant swarm over a long course of time, it must be capable of self-replenishment. Engineers at the University of Southampton recently launched a 3D printed drone off a British Navy warship. The four-foot aircraft was capable of flying 60 miles per hour and took 24 hours to build.[85] This type of approach could radically redefine the traditional logistical model with a just-in-time model in which bulk raw materials are used near the theater of operations to create units specifically tailored to the requirements of the battle-space.

By building a swarm that is both low-cost and effective, the U.S. can implement a strategy that advantageous cost-exchange over an adversary. Simplified, the swarm acts to continually attrit the enemy's defensive ammunition. When combined with the current strategy that uses low-observable, stealth aircraft, the synergy would be far more capable of defeating an adversaries' A2/AD. By undermining the adversary's strategy, the military would be far more coercive.

Risks

The goal of this paper is to address how swarming may be able to mitigate the risks associated with fighting a war of attrition. However, the implementation of a swarming strategy would create new risks that must be considered. First, the majority of the technology used to illustrate the requirements is predominantly from the commercial sector. This means there are low barriers to entry and that swarming could be potentially used by adversaries against the United States. Second, the U.S. Air Force is currently in the process of modernizing the majority of its legacy weapons systems and has no official plans in place for the development of the kind of small unmanned aerial systems (SUAS) that would be required for a swarm. This type of disruptive technology presents an "innovator's dilemma"[86] to a large military force with a great deal of inertia towards fighting wars of annihilation and not attrition. Third, the use of swarms, much like the use of unarmed systems today, will garner a great deal of public opposition. The thought of an autonomous system killing without a human-in-the-loop is often criticized and swarming would only exacerbate this opposition. Finally, no strategy is deterministic or prescriptive. War is a human endeavor, and neither actor operates rationally once fighting escalates. As Clausewitz warns, war tends to be dictated by passion and chance so it is never safe to assume that an adversary will respond in accordance with our predictions.

Conclusion

The United States wants to fight a war of annihilation because it is well suited to do so. However, the U.S.'s adversaries have a vote in this and have decided that it is in their own best interest to prevent the U.S. from being able to fight such a war. Rather, the adversaries have adopted A2/AD strategies that would force the U.S. to fight an undesirable war of attrition in order to achieve their objective. The current strategy to counter A2/AD is a strategy that forces the tenets of an annihilation strategy into the context of an attrition environment. The result is that it weakens the military as an instrument of national power. The U.S. military should consider swarming as both an effective and efficient strategy for fighting wars of attrition. By incorporating a swarming force into the current strategy, the U.S. military will provide better deterrence and be more coercive during conflict. With those objectives in mind, there are many considerations for how the swarm should be developed and employed. First, the swarm must be attrition tolerant. This can be achieved by utilizing fractionated mass and disposable, unmanned units. Second, the swarm must be low-cost, autonomous, modular, and adaptable. These technologies already exist in the commercial sector.

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[52] Werner J.A. Dahm, "Survivability Benefits of System Architectures Based on Fractionation with Redundancy," *White Paper AF/ST-09-0013* (Pentagon: Chief Scientist of the U.S. Air Force (AF/ST), Aug 2009), equation 6 and the "Aside" from pg. 3.
[53] Ibid, equation 2, The defender's high confidence in a swarm mission failure is defined as $P_L = 0.95$ and subsequently a $P_S = 0.05$.

[54] Ibid, equation 9, $P_L = 0.95$, $P_K = 0.9$, n = 10. This represents a highly capable A2/AD defensive system ($P_K = 0.9$) with a high confidence by the defender ($P_L = 0.95$) that the attacker's 10-unit swarm will be completely destroyed.

[55] Ibid, $P_L = 0.95$, $P_K = 0.9$, n = 100 results in N = 329. This is an increase in swarm size over the ten units in the previous note to 100 units while holding constant the high capability of the A2/AD defense and a defenders high confidence.

[56] Ibid, $P_K = 0.9$ and n = 100. Confidence of mission failure (P_L) is input at 0.4 resulting in N = 200 required shots. P_L is then input at 0.1 resulting in N = 150 shots. Because the solution is mathematically unique, the reverse logic is also valid. Therefore, if only 200 shots are fired the defender may hope for a higher confidence but realistically can only attain a 0.4 confidence of mission failure.

[57] General Ralph Jodice served as NATO's Air Component Commander during Operation Unified Protector. In several speeches he has mentioned how the MQ-1 was able to destroy an Libyan surface to air missile and that the feat marked the first time an RPA had performed a destruction of enemy air defense (DEAD) mission.

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[64] See Note 46.

[65] This example is operationally relevant. The newest of Russian surface-to-air missile system, the S-400, advertises a total of 384 missiles per system. http://missilethreat.wpengine.netdna-cdn.com/wp-content/uploads/2013/03/s-400.png

[66] Tamir Eshel, "How Dangerous is the S-300 Syria is About to Receive," http://defense-update.com/20130518_how-dangerous-is-the-s-300.html

[67] Werner J.A. Dahm, *White Paper,* equation 9. Dividing N = 329 shots by n = 100 swarm units gives a ratio of 3.29 shots per swarm unit. For instance, the 9M96 missile (SA-20 Gargoyle) costs $1M per missile (previous note). Multiplying $1M per "shot" by 3.29 shots per swarm unit results in $3.29M per swarm unit.

[68] Paul Scharre, *Robotics on the Battlefield Part II: The Coming Swarm*, Center for a New American Security, (October, 2014), 21.

[69] Undersecretary of Defense Comptroller, "FY2011 Program Acquisition Costs by Weapon System," pg. 1-2, http://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2011/FY2011_Weapons.pdf

[70] Office of the US Air Force Chief Scientist, *Technology Horizons, A Vision for Air Force Science and Technology* (Maxwell AFB, AL: Air university Press, 2011), 54-55.

[71] Ibid., 55.

[72] It is important to note that the book *Technology Horizons*, pg. 55, states that "when a fractionated architecture is augmented by even low levels of redundancy among the dispersed elements, *survivability can increase dramatically*" [emphasis added]. The analysis in this paper seems to imply exactly the opposite. However, Dr. Dahm's notes in "Survivability Benefits of System Architectures Based on Fractionation with Redundancy," *White Paper AF/ST-09-0013* from the "Aside" on pg. 3 that the "benefit of redundancy for integrated systems is weak when P_K values

are realistically large." The analysis in this paper invokes these large P_K values and so discovers the weak benefits as described by Dr. Dahm.

[73] Werner J.A. Dahm, *White Paper*, equation 14, $P_L = 0.95$, $P_K = 0.9$, $n = 50$, $m = 2$. The 100-unit swarm is now fractionated into two equal groups of 50 units each consisting of sensors and shooters.

[74] See note 46.

[75] The result of note 74 is N = 230 shots; a reduction in required shots from the unfractionated swarm.

[76] Werner J.A. Dahm, *White Paper*, equation 14. Calculated twice using $P_L = 0.95$, $P_K = 0.9$, $m = 3$ and $n = 33$ (total of 99 units), and $m = 4$ and $n = 25$ (total of 100 units) resulting in $N = 184$ and $N = 160$ required shots, respectively. This compares fractionation effects for constant swarm sizes.

[77] Ibid. Using $P_L = 0.95$, $P_K = 0.9$. The variant number is set to m = 2 and the value for n increased from n = 50 to an "n" that was close to 329 shots (N = 330 shots in this case); the result was n = 68 giving 136 swarm units.

[78] Ibid. Using $P_L = 0.95$, $P_K = 0.9$. The variant number is set to m = 3 and the value for n increased from n = 33 to an "n" that was close to 329 shots (N = 336 shots in this case); the result was n = 54 giving 162 swarm units. Likewise, the same process is run for m = 4 variants resulting in n = 45, 180 swarm units, and giving N = 333 shots.

[79] See note 68. Dividing N = 329 shots by 136 swarm units gives a ratio of 2.42 shots per swarm unit.

[80] Ibid., equation 14. Using $P_L = 0.95$, $P_K = 0.9$, the "m" value and "n" value are set as indicated in the table. The resulting "N" shots are calculated in the background and divided by the total number of units in the table. Using the process in Note 68, the cost per missile (shot) is multiplied by the shots per unit and the max cost per unit is found.

[81] Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability*, 9-10.

[82] "To Print a Missile: Raytheon Research Points to 3-D Printing for Tomorrow's Technology," Raytheon.com. updated 11 Nov 2015, retrieved online 19 Mar 2016 from http://www.raytheon.com/news/feature/3d_printing.html

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[86] Clayton M. Christensen popularized the term "innovator's dilemma" to explain why large organizations fail to innovate. *The Innovator's Dilemma*, (New York: Harper Business, 1997)